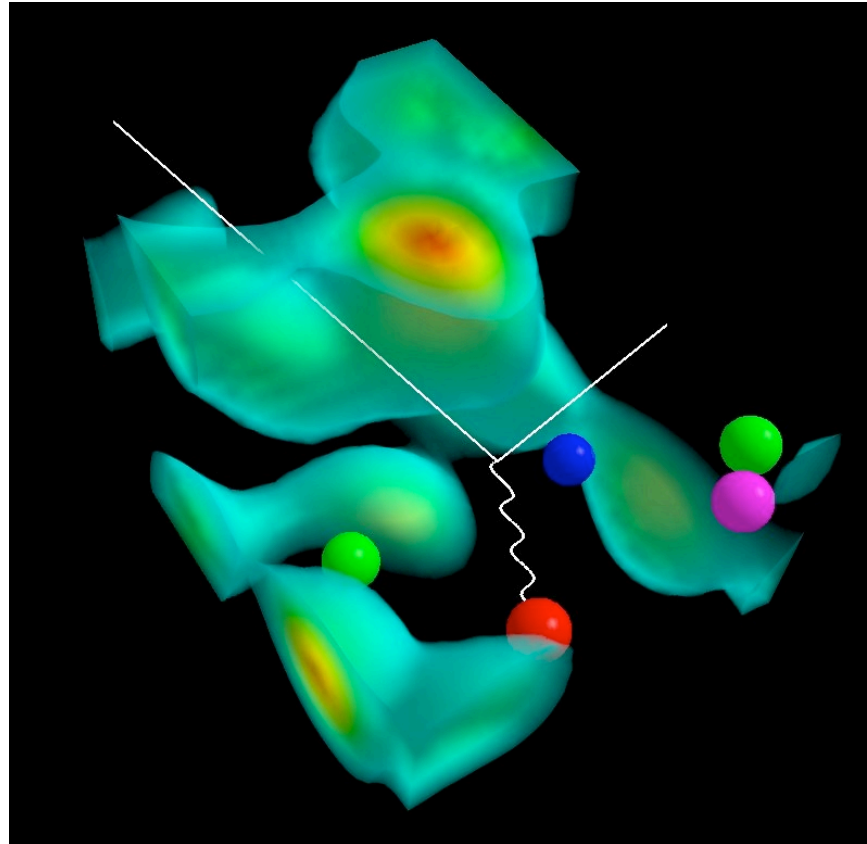


Theoretical Physics at JLab



David Richards

JSA Science Council

April, 2007

Outline

- **Why a Theory Center at Jefferson Lab?**
- **Who are the members?**
- **What they do – overview**
- **Highlights and Initiatives**
 - **Theory in concert with Experimental Program**
 - **EBAC**
 - **Lattice QCD**
- **Summary**

Key Roles of Theory at JLab

- **Contribute to Intellectual Leadership of Lab**
 - **NSAC Long-range Plan**
- **Phenomenological Support of Experimental Program**
 - development/analysis of proposals
 - essential support in interpretation of data
- **Projects of scope/duration appropriate to a national laboratory: *EBAC, Lattice QCD***
- **Education and Development of graduate students and postdoctoral fellows –**
 - **HUGS** (*Hampton University Graduate School*).
 - *Theory-Group mini-lectures* (*Erlich, Epelbaum*)
 - **Graduate-level Hadronic Physics** (*Melnitchouk*)

JLab Theory Center: Senior Staff

- **5 Laboratory staff (4.5 FTE)**

Robert Edwards	lattice gauge theory
Franz Gross	(0.5 time)
Wally Melnitchouk	phenomenology
David Richards	Deputy Director (lattice gauge theory)
Christian Weiss	phenomenology

Distinguished Visitors: S. Brodsky, W. Bentz, D. Diakonov, V. Flambaum, P. Guichon, B. Holstein, D. Leinweber, G. Miller, M. Peardon, A. Sibirtsev, J. Tjon....

Chief Scientist / Director: Anthony Thomas

- **8 staff with joint appointments (4.0 FTE) 50 % Lab support)**

Ian Balitsky (ODU)	Jozef Dudek (ODU)
Jose Goity (Hampton)	Rocco Schiavilla (ODU)
Kostas Orginos (W&M)	Marc Vanderhaeghen (W&M)
Anatoly Radyushkin (ODU)	Wally van Orden (ODU)

JLab Theory Group: Junior Staff

- 4 JLab postdoctoral fellows (4 FTE)

HueyWen Lin (PhD 06, Columbia) – since Oct 06

Marc Schlegel (PhD 05, Bochum) - from Oct 03

Nilmani Mathur (PhD 00, RPI) - from July 05

Ross Young (PhD 04, Adelaide) – from Oct 04

← Tata faculty

← Wigner fellow,
ANL

- Isgur Distinguished Postdoctoral Fellow

Evgeny Epelbaum (Ph.D. 00, Bochum) – Oct 03 to Mar 06

Joint position between Juelich and University of Bonn.

Search in Progress

JLab Theory Group: Associate Staff

- 4 senior staff (100% university support)

Carl Carlson (W&M)

Marc Sher (W&M)

Chris Carone (W&M)

Peter Agbakpe (NSU)

- **12 graduate students:**

8 supported by JLab (includes 2 LSU)

- **Bridge Positions:**

New bridge positions with University of Virginia (Chris Dawson) and with Hampton University, and with Beijing University

- **Joint post-doctoral position in phenomenology with Hampton University**

Joint and Bridge Positions vital in attracting graduate students

Distinguished Staff

- 8 Fellows of the American Physical Society;
1 Fellow Australian Academy of Science and IoP
Wally Melnitchouk (2007 APS Fellow)
Kostas Orginos (2007 OJI)
- Serve on IAC of every major conference/workshop in related fields:
- Organization and planning of major workshops
 - *DNP 2007, Lattice 2008*



Marciana Marina, Isola d'Elba, Italy.

Electron-Nucleus Scattering IX Workshop, June 19-23, 2006

December, 1-3 2005
Newport News, VA USA

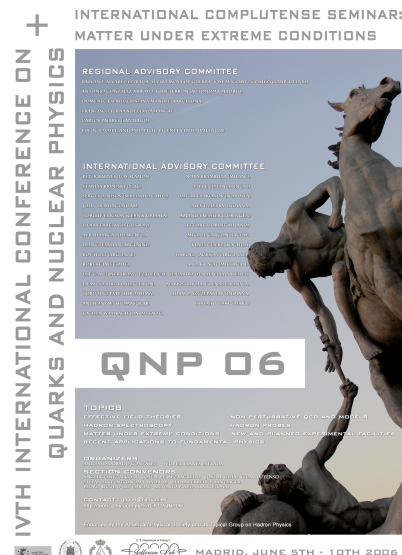
Cascade Physics: A New Window on Baryon Spectroscopy

The workshop will explore the uncharted area of hadron physics in systems of double strangeness.

Topics include:
Theoretical Motivations
Cascade resonances on the lattice
Experimental Status
Extraction of Cascade Properties
Masses and widths
Spin-parity
Production Mechanisms
Decay modes
Tests of Sum rules
s, u, d Quark Masses
Experimental Program
Requirements of new

Organizers:
Dennis Weygand, JLab
Ben Nefkens, UCLA
John Price, CSUDH

conferences.jlab.org
for more information contact



LATTICE 2006 THE INTERNATIONAL SYMPOSIUM



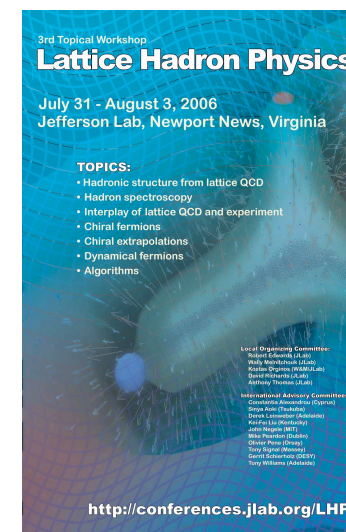
Tucson, Arizona
July 23rd to July 28th
Lodging and meetings
will be held at the
Starr Pass Resort



Topics:
Algorithms, Machines, and Networks
Beyond QCD: large N, Regge, SU(2) Gravity, Strings
Chiral Symmetry
Confinement
Electroweak Decay and Mixing
Hadron Spectroscopy
Hadronic Interactions and Structure
High Temperature and Density
Quark Masses, Gauge Couplings, and Renormalization
Theoretical Developments

www.physics.arizona.edu/lattice06

HOSTED BY THE UNIVERSITY OF ARIZONA



Theory Group Research Activity - I

➤ How quarks and gluons form hadrons and nuclei:

- Solving QCD in the nonperturbative regime:
 - **Lattice Gauge Theory** (Dudek, Edwards, Lin, Mathur, Melnitchouk, Orginos, Richards, Thomas, Young)
- Solving QCD at the boundary between perturbative and nonperturbative regimes:
 - **Sum rule techniques** (Balitsky, Radyushkin)
 - **Hadronic form factors, parton distribution functions, and duality** (Balitsky, Carlson, Edwards, Mathur, Melnitchouk, Radyushkin, Richards, Schlegel, Vanderhaeghen, Weiss, Young)
 - **QCD at high densities** (Balitsky)
- Understanding/modeling the confinement and structure of hadrons and nuclei :
 - **Heavy-quark effective theory** (Goity)
 - **Chiral dynamics and large N_c QCD** (Carone, Goity, Gross, Thomas, Young)
 - **Relativistic and nonrelativistic quark models** (Dudek, Goity, Gross, Van Orden, Thomas)

Theory Group Research Activity - II

➤ How nucleons bind together to form nuclei

- Constructing nuclear interactions and currents:
 - One-boson-exchange phenomenology and similar (Gross, Schiavilla, Van Orden)
 - Effective field theory approach (Thomas, Young)
 - Hadronic interactions in Lattice QCD (Orginos)
- Structure and reactions of nuclei:
 - Relativistic approaches to nuclear dynamics (Gross, Schiavilla, Thomas, Van Orden)
 - Form factors and weak transitions in few-nucleon systems (Gross, Schiavilla, Thomas, Van Orden)
 - EFT studies of the structure of few-nucleon systems (Gross, Schiavilla)
 - Nuclear reactions of astrophysical interest (Schiavilla)

Theory Group Research Activity - III

➤ The Standard Model and beyond

(Carlson, Carone, Sher, Thomas, Young)

- Constraints on lepton-flavor mixing from experiments
 - TeV-scale physics in low-energy parity violating observables
 - CP Violation
 - Time dependent coupling “constants” as tests of extra dimensions
 - NuTeV “anomaly” : charge symmetry violation of PDFs
 - Theory support for Qweak
- PAC involvement: (ALL members – including post-docs)

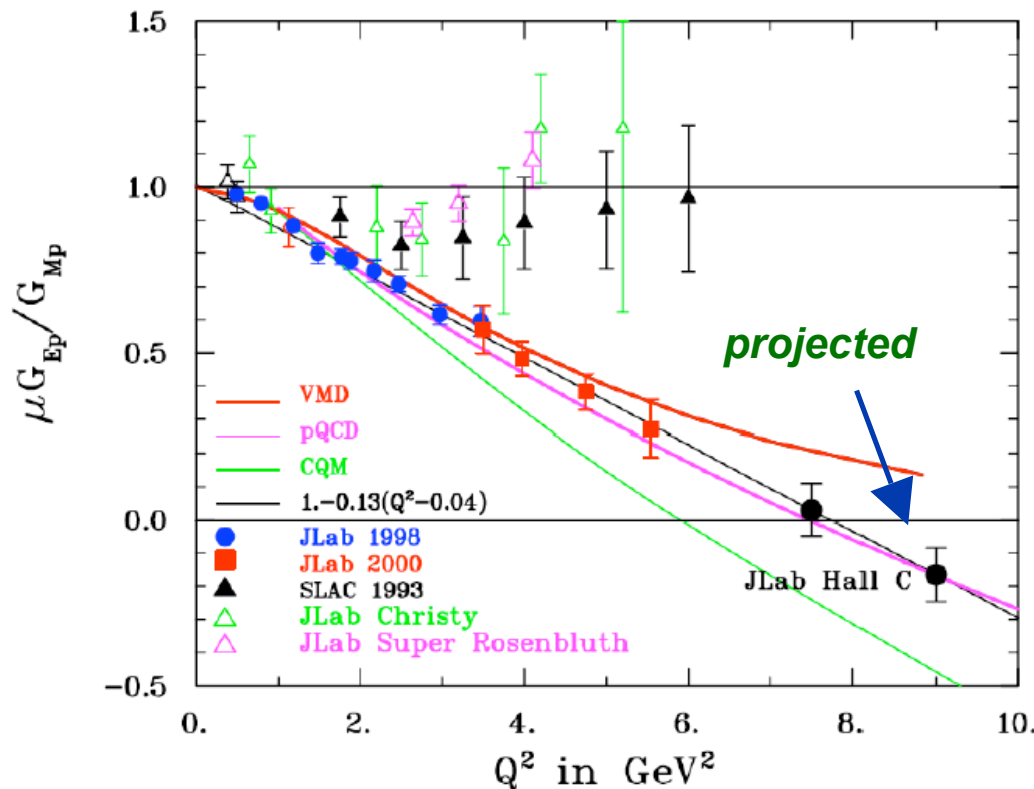
Deliver written reports to PAC on every new proposed experiment – viewed as extremely valuable by PAC members.

➤ Physics Program for the 12GeV Upgrade

Highlights: Theory in Concert with the Experimental Program

Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon

HP 2010

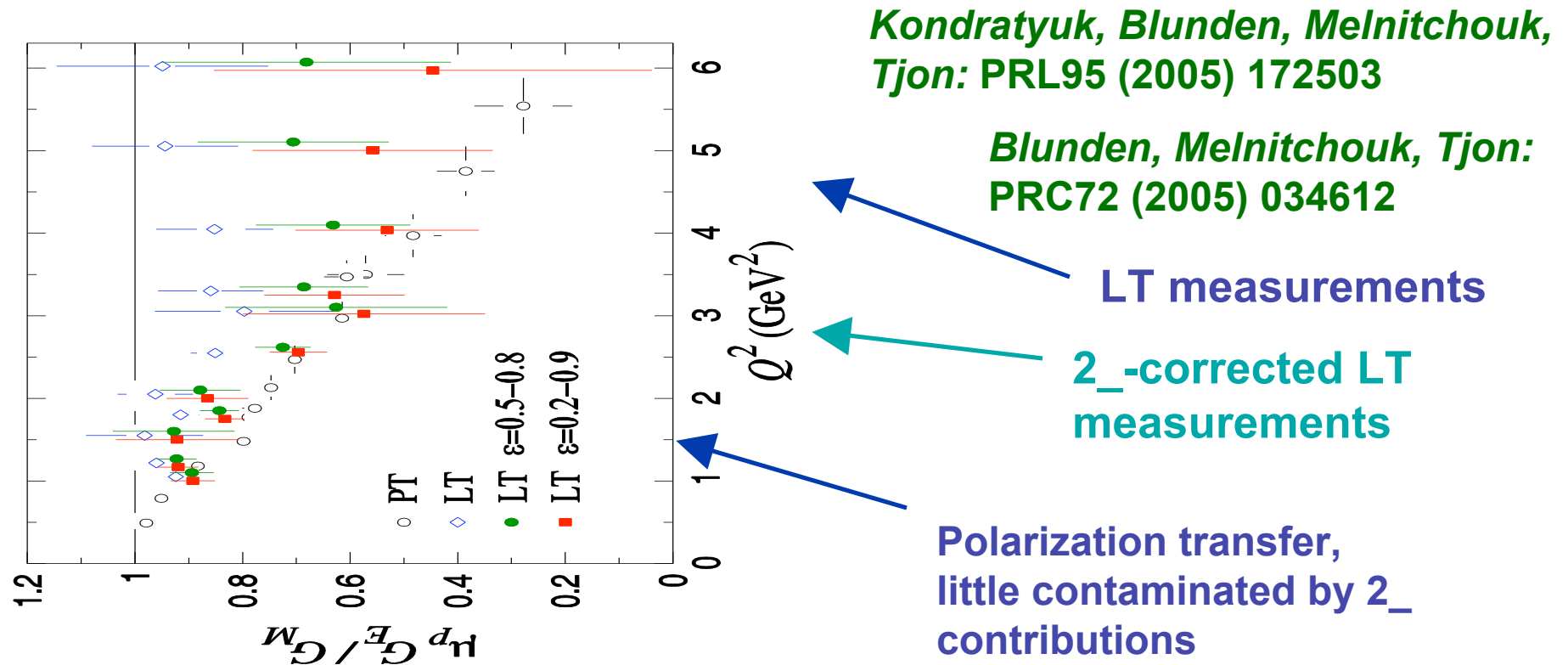


Precise experimental measurement to confront lattice data

Need to resolve polarization-transfer and LT-separation measurements

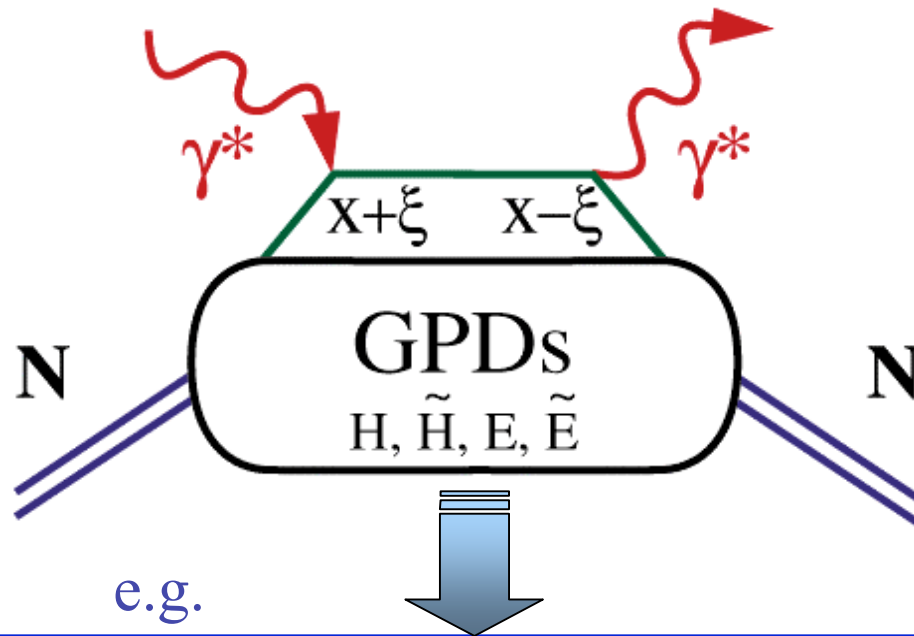
C. Perdrisat (W&M), JLab Users Group Meeting, June 2005

Two-photon exchange calculation



Ongoing work by **Melnitchouk** and **Arrington** to analyze global ep data ! **most accurate determination of G_E and G_M**

Generalized Parton Distributions (GPDs): New Insight into Hadron Structure



HP 2008

X. Ji &
A. Radyushkin
(1996),
D. Müller (1993)

Quark angular momentum (Ji's sum rule)

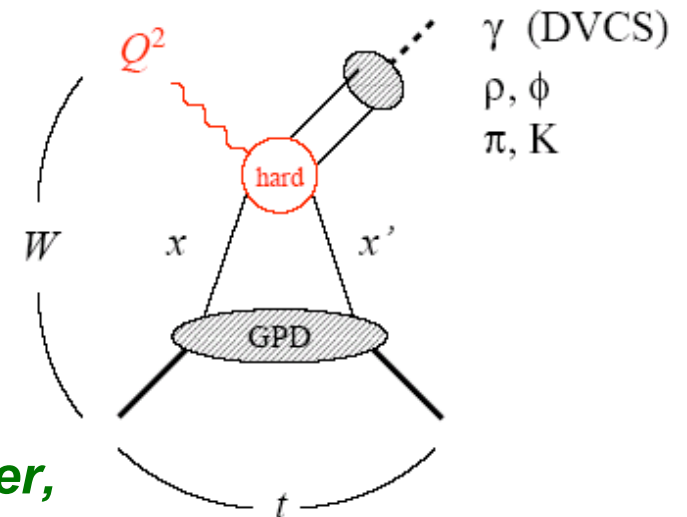
$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^1 x dx [H^q(x, \xi, 0) + E^q(x, \xi, 0)]$$

X. Ji, Phys.Rev.Lett.78,610(1997)

Major review by *Belitsky and Radyushkin*, Phys. Rep. 418 (2005), 1-387

GPDs: Phenomenology of hard exclusive processes in eN Scattering

- $Q^2, W \gg 1$: QCD factorization
- Aim: extract information from data about GPDs at finite Q^2, W .
- *This requires significant theory input!*
- Study uncertainties in model predictions for leading-twist amplitudes – *Diehl, Kugler, Schafer, Weiss, PRD72, 034034 (2005)*
- Review of high-energy data at HERA
 - Higher-twist & hadronic structure of photon
 - Successful gluon imaging of proton

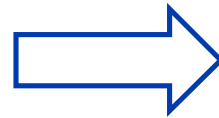


Frankfurt, Strikman, Weiss, Ann. Rev. Nucl. Part. Sci. 55, 403 (2005)

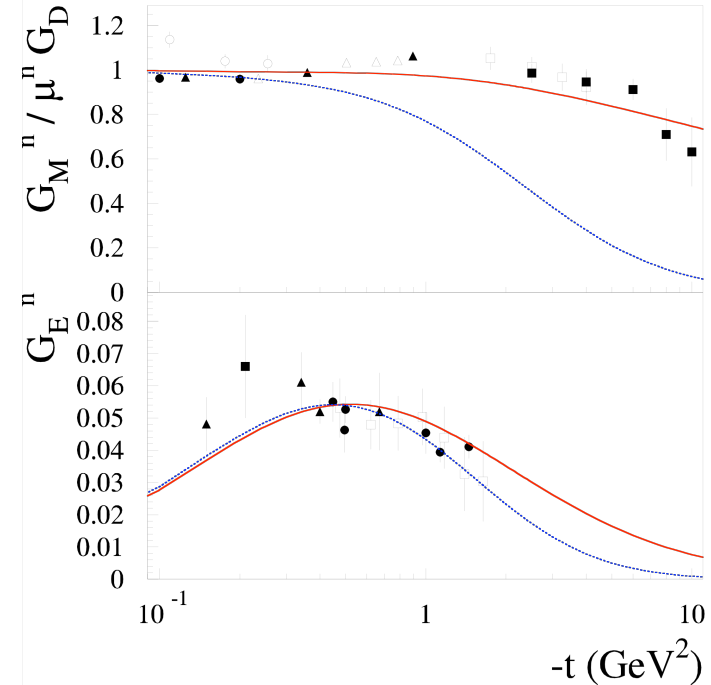
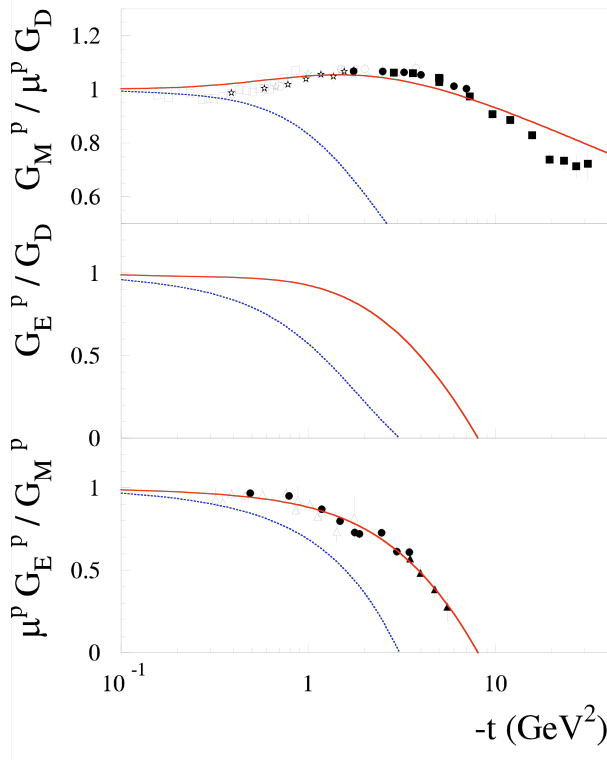
Develop techniques for GPD analysis of exclusive reactions at JLab@12 GeV

Modeling GPD's

Links between GPDs and FFs explored, using Regge param. at small t .



Description of the four p and n form factors.

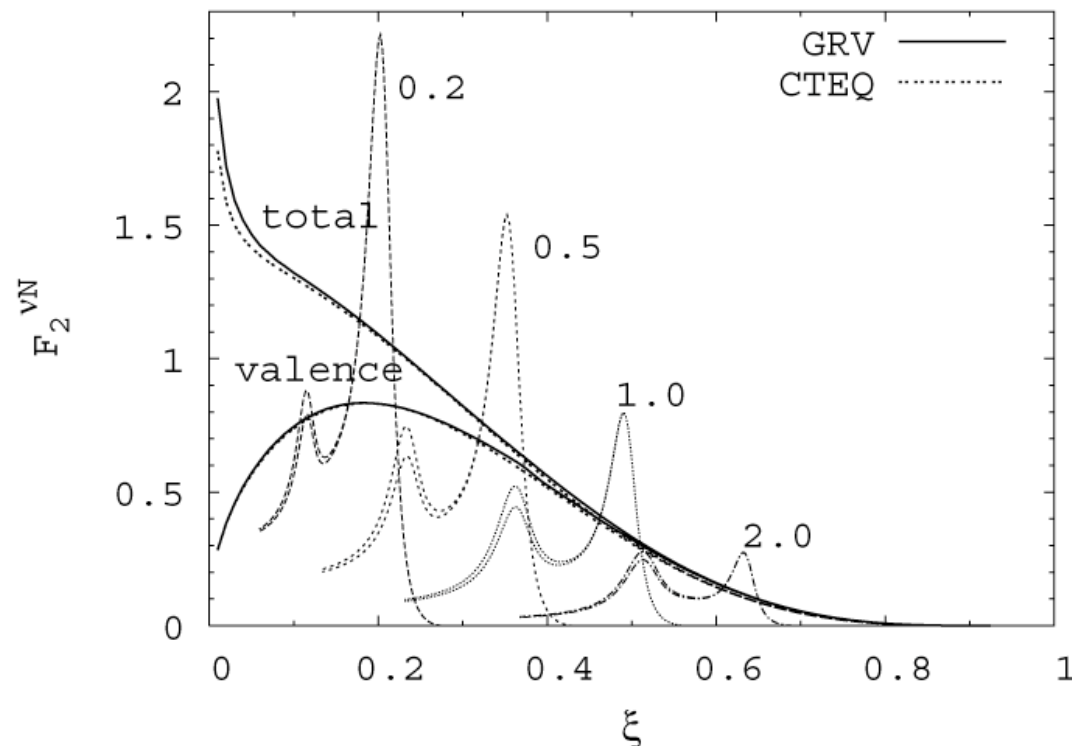


Guidal, Polyakov, Radyushkin, Vanderhaeghen, PRD72 (2005), 054013

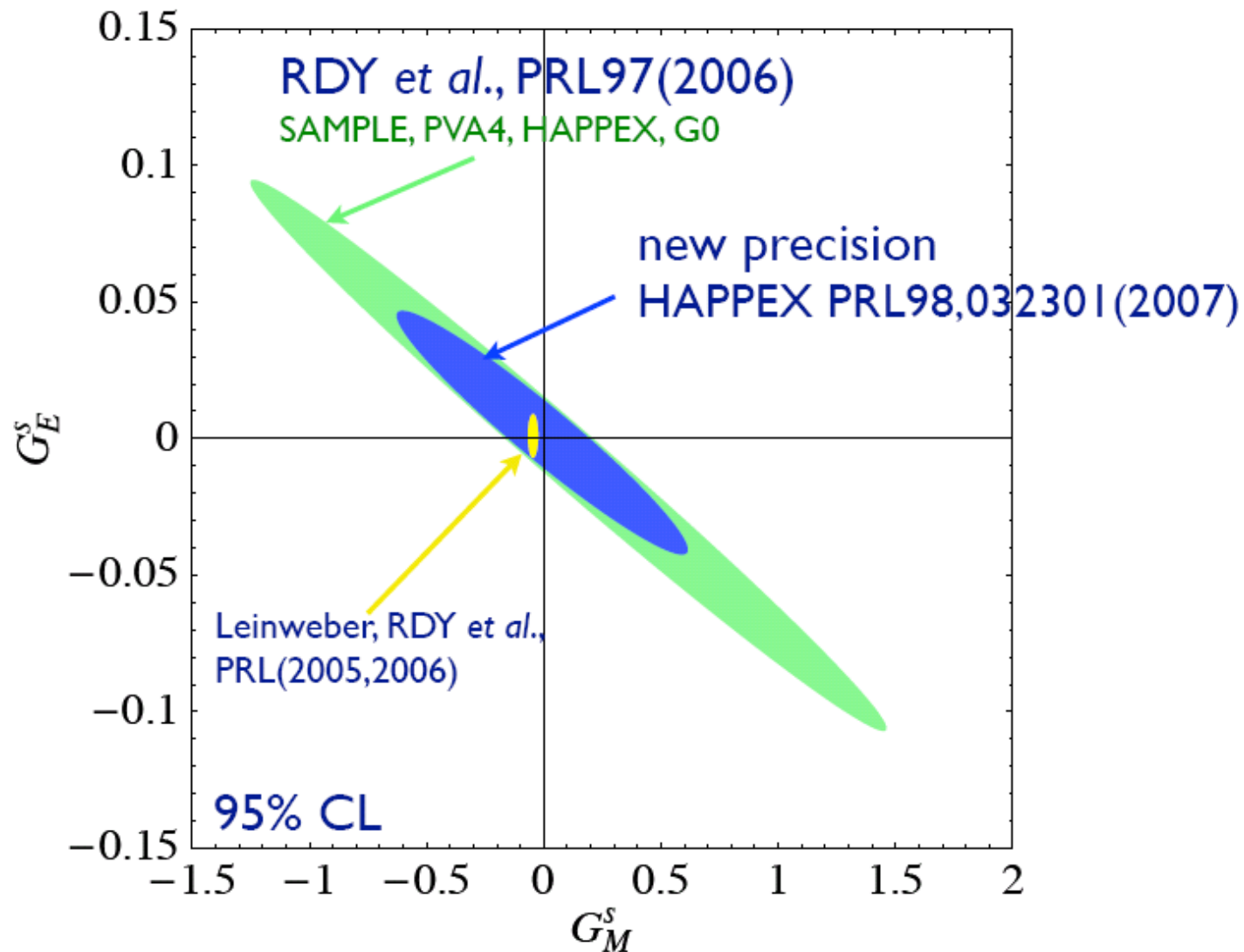
Duality in νN Scattering

- Studies of duality extended from $e N$ to νN scattering
- Appears to be exhibited in F_2 and F_3 structure functions, but less for F_1

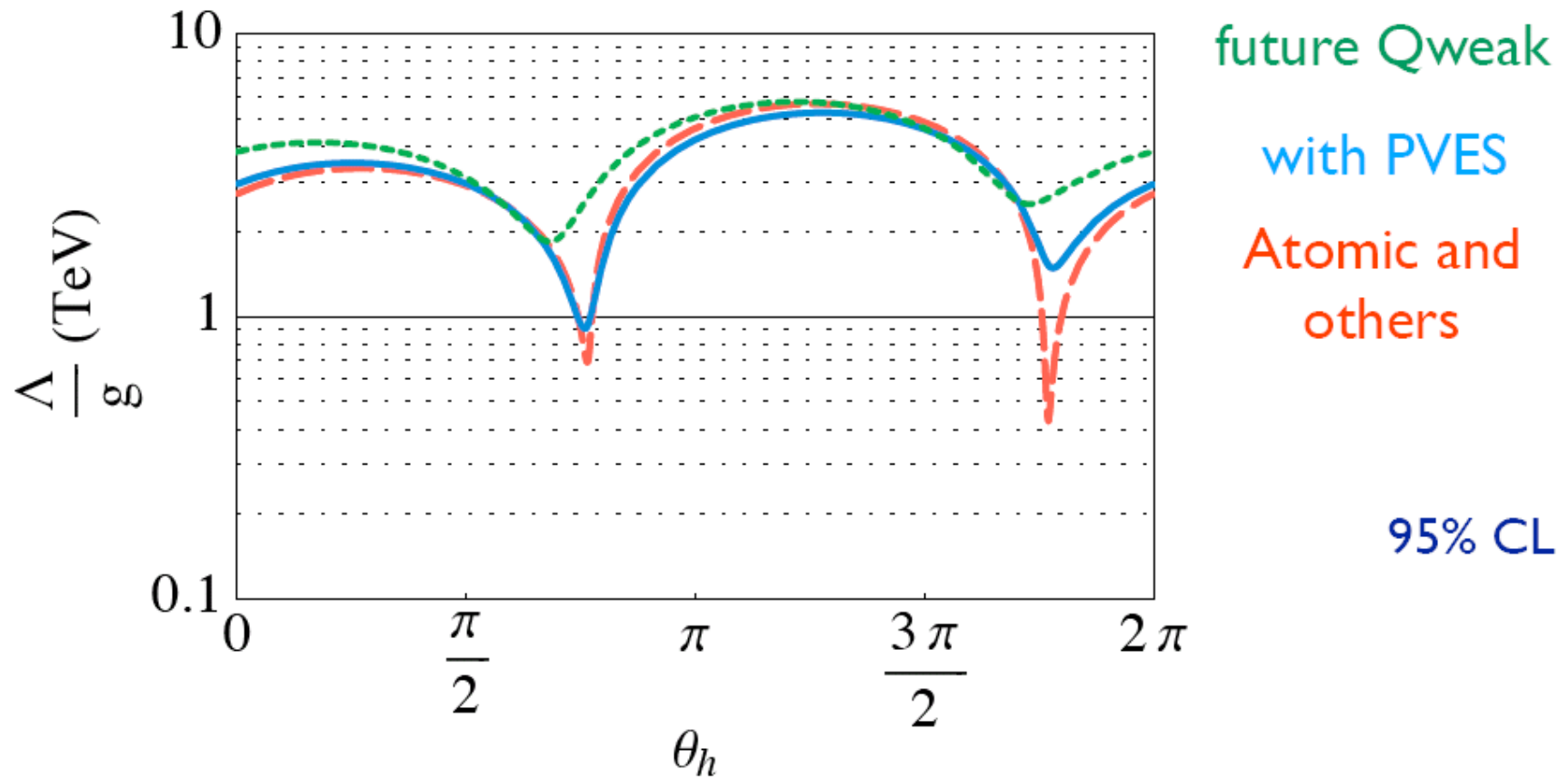
Lalakulich et al,
PRC75, 015202
(2007)



Strangeness: global analysis of PVES experiments



PVES: Search for New Physics



QWEAK will constrain new physics to beyond 2 TeV

Excited Baryon Analysis Center (**EBAC**)

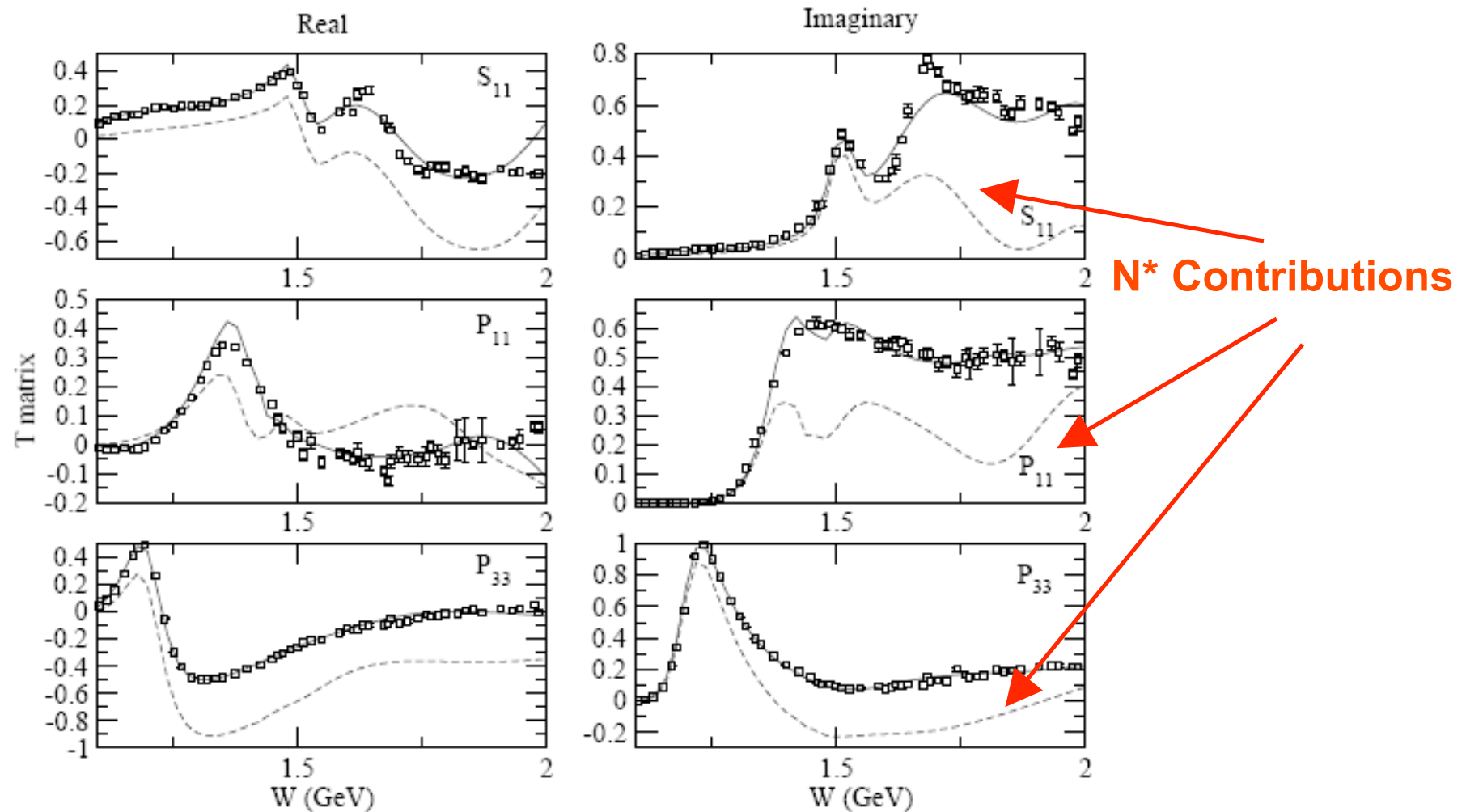
- **Established:** January 2006
- **Members:** Harry Lee (50/50 ANL), Mark Paris (PDF)
+ 2 PDFs Summer 2007
- **Goal:** Reach at DOE **Milestone** by 2009

“Complete the combined analysis of available single pion, eta and kaon photo-production data for nucleon resonances and incorporate analysis of two-pion final states into the coupled channel analysis of resonances.”

EBAC - II

- On-going theoretical projects:
 - Perform dynamical coupled-channel analysis (Julia-Diaz *et al*)
 - πN , ηN , $\pi\pi N$ production
 - ωN , $K \Lambda$ production
 - Develop collaborations with other theoretical efforts
 - Coupled-channel analysis by **Julich** group (Haidenbauer *et al*).
 - **EBAC-Saclay** coupled-channel analysis of η , K photoproduction (David *et al*).
- Provide theoretical input to data analyses by experimental groups
- Projects being developed:
 - Reaction models at **high Q^2** , accessible to **12 GeV upgrade**
 - Investigation of connections with **Lattice QCD**.

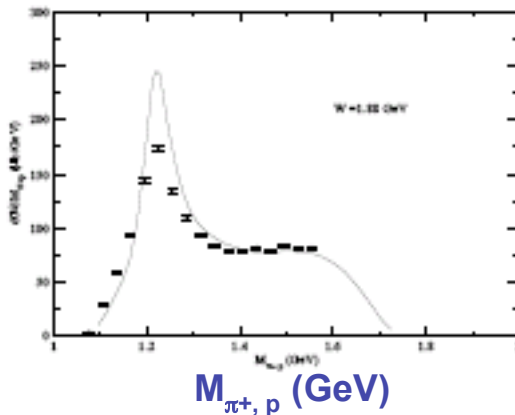
EBAC: First Results - I



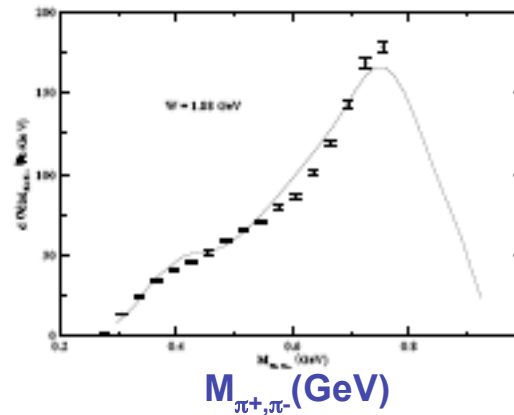
EBAC: First Results - II

- Start to analyse γ **p** ! π^+ π^- **p** JLab data

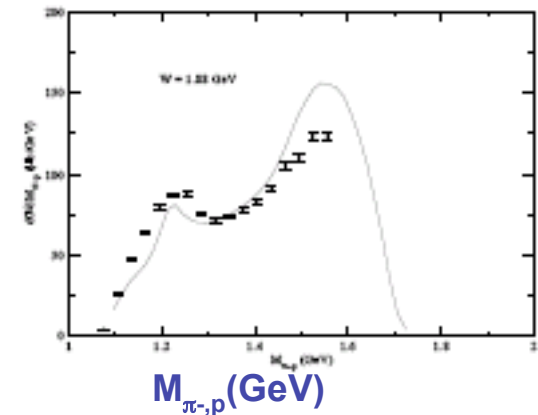
$d\sigma/M_{\pi^+, p} (\mu \text{ b/GeV})$



$d\sigma/M_{\pi^+, \pi^-} \text{ GeV} (\mu \text{ b/GeV})$



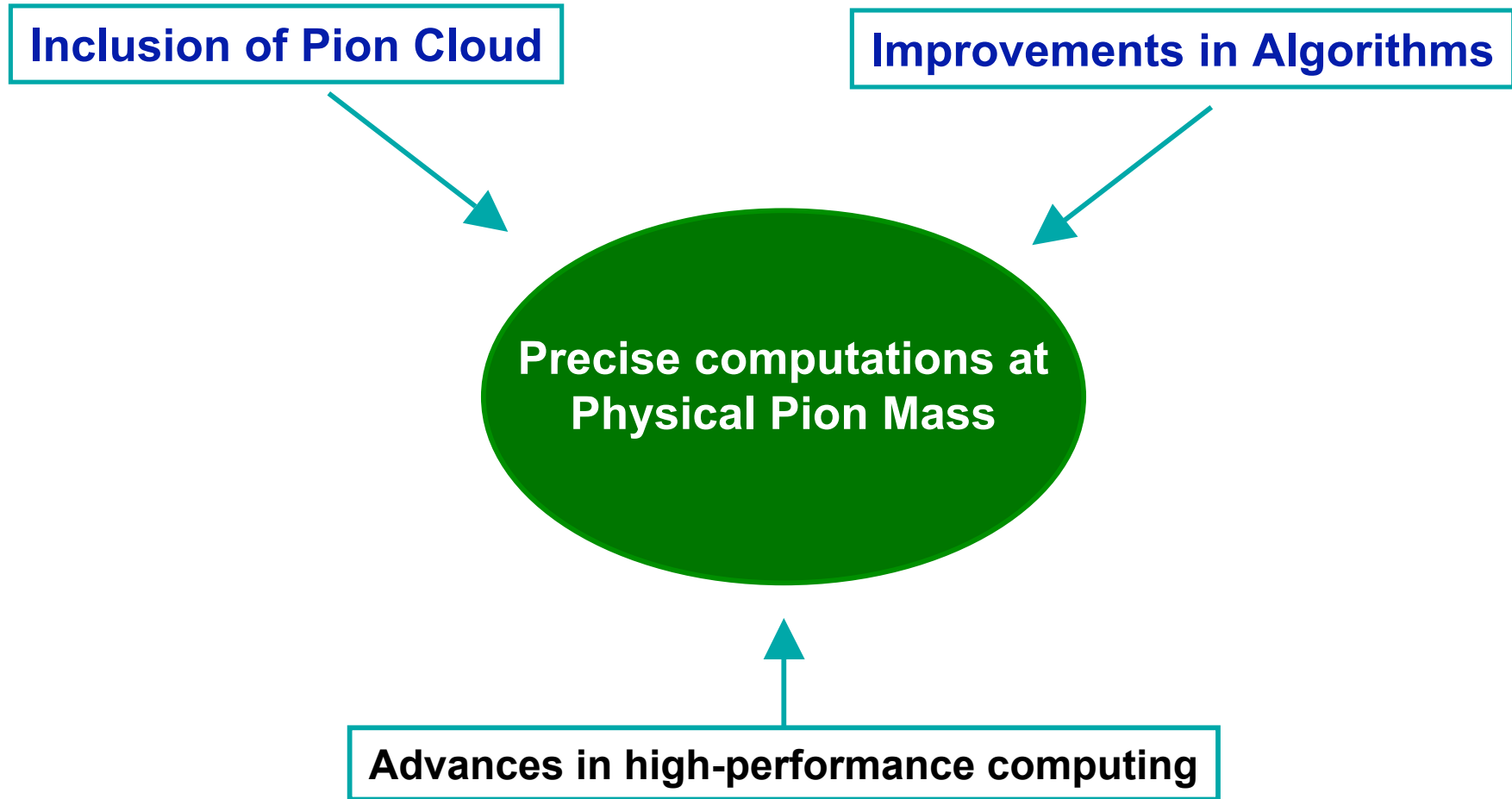
$d\sigma/M_{\pi^-, p} \text{ GeV} (\mu \text{ b/GeV})$



- Plans:

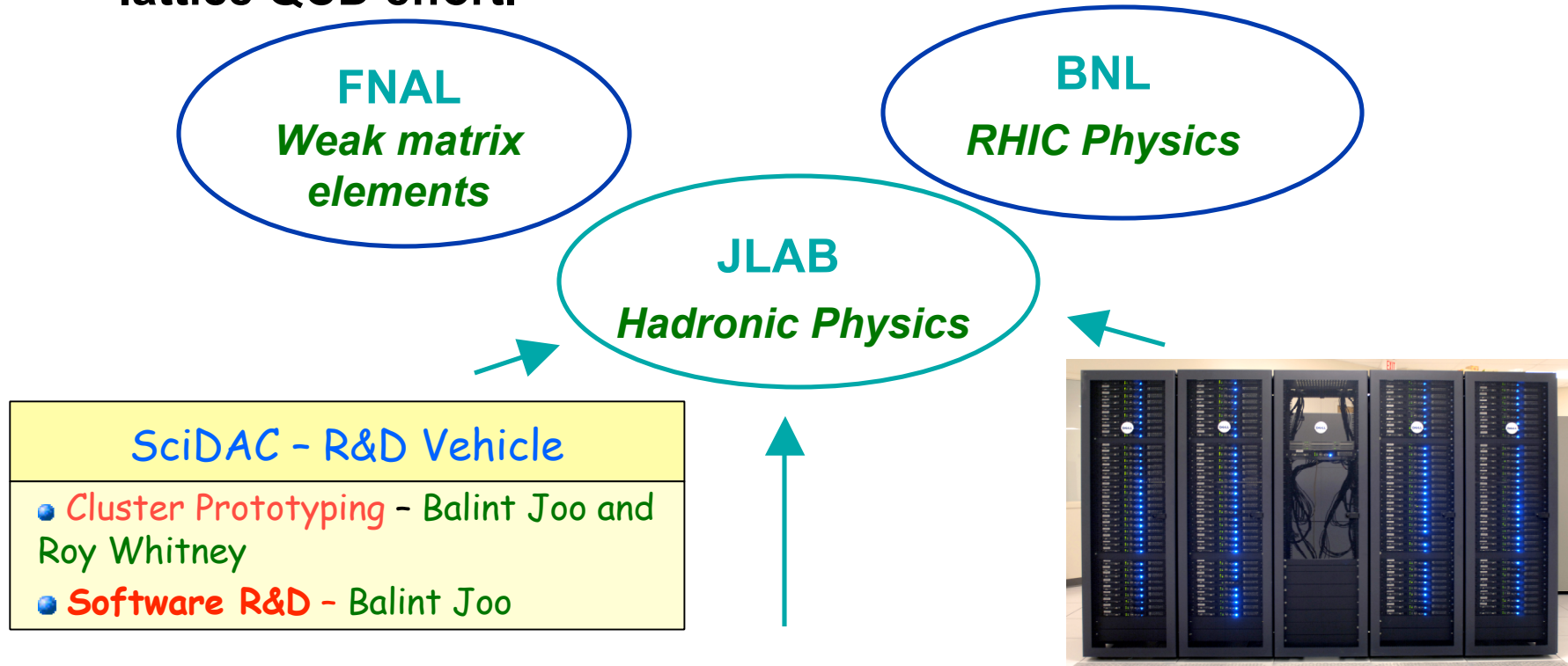
- **2007**: Analysis of π , η , $\pi \pi$ production data
- **2008**: Full coupled analysis, including ω , **K** production data

Lattice QCD



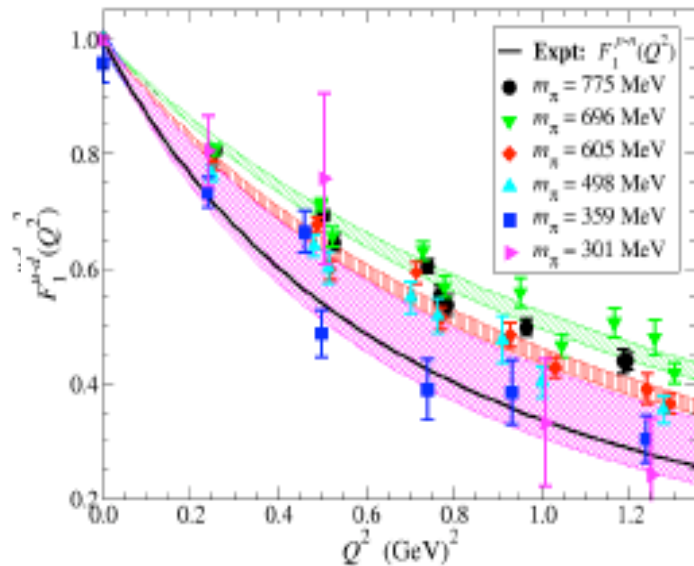
JLab and National Effort

- Jefferson Laboratory co-equal partner with BNL and FNAL in lattice QCD effort.



Lattice QCD at JLab having critical impact on JLab's Nuclear Physics Program

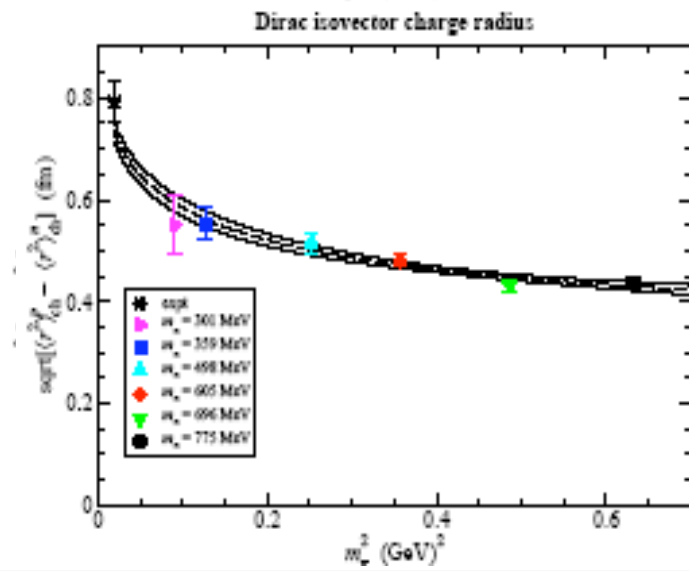
Lattice: Proton EM Form Factors



- Lattice QCD computes the *isovector* form factor
- Hence obtain Dirac charge radius $\langle r^2 \rangle_{ch}^{u-d}$ assuming dipole form
- Chiral extrap. Using LNA and LA terms and finite-range regulator.

Leinweber, Thomas, Young, PRL86, 5011

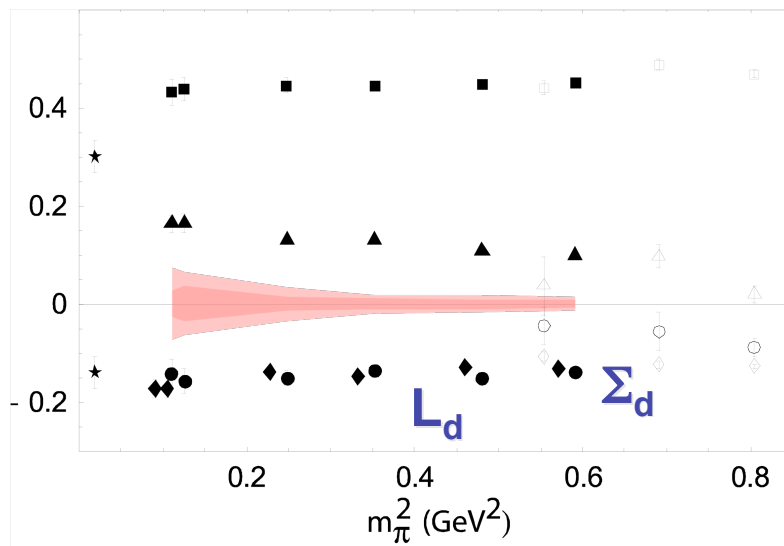
- As the pion mass approaches the physical value, the size approaches the correct value



$$\langle r^2 \rangle_{ch}^{u-d} = a_0 - 2 \frac{(1 + 5g_A^2)}{(4\pi f_\pi)^2} \frac{1}{2} \log \left(\frac{m_\pi^2}{m_\pi^2 + \Lambda^2} \right)$$

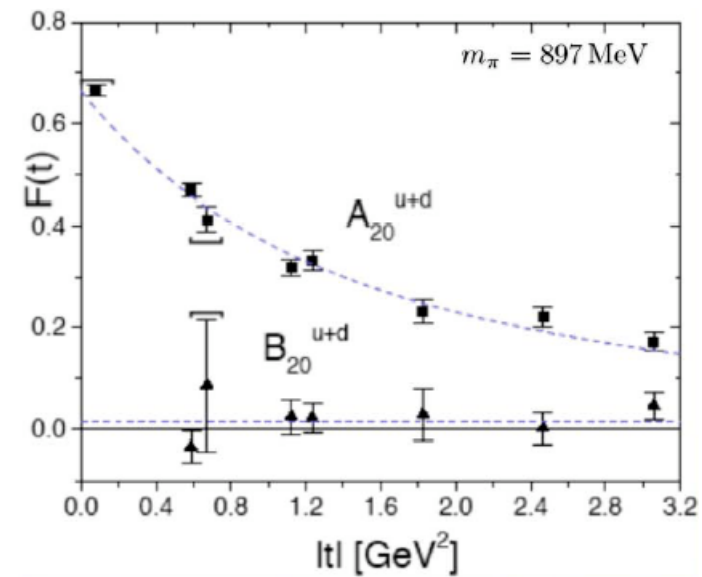
Lattice: Origin of Nucleon Spin

- How is the spin of the nucleon divided between quark spin, gluon spin and orbital angular momentum?
- “Spin Crisis” or EMC effect...
- Ji’s sum rule enables us to determine **total angular momentum carried by quarks in nucleon**



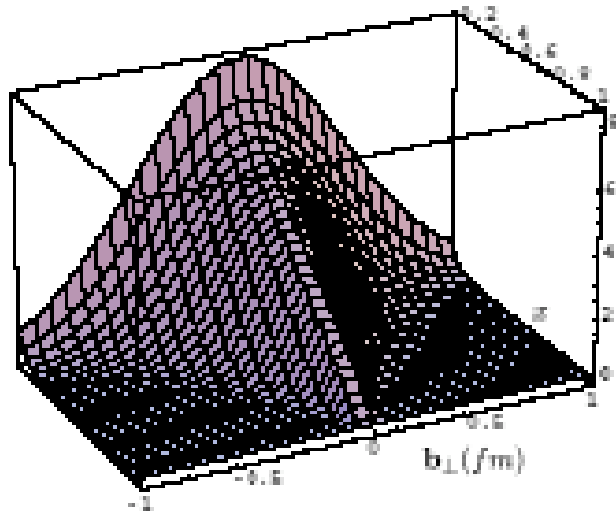
$$J_q = \frac{1}{2} [A_{20}(0) + B_{20}(0)]$$

$$\frac{1}{2} \Sigma = \frac{1}{2} [\langle 1 \rangle_{\Delta u} + \langle 1 \rangle_{\Delta d}]$$



Quarks have negligible angular momentum in nucleon

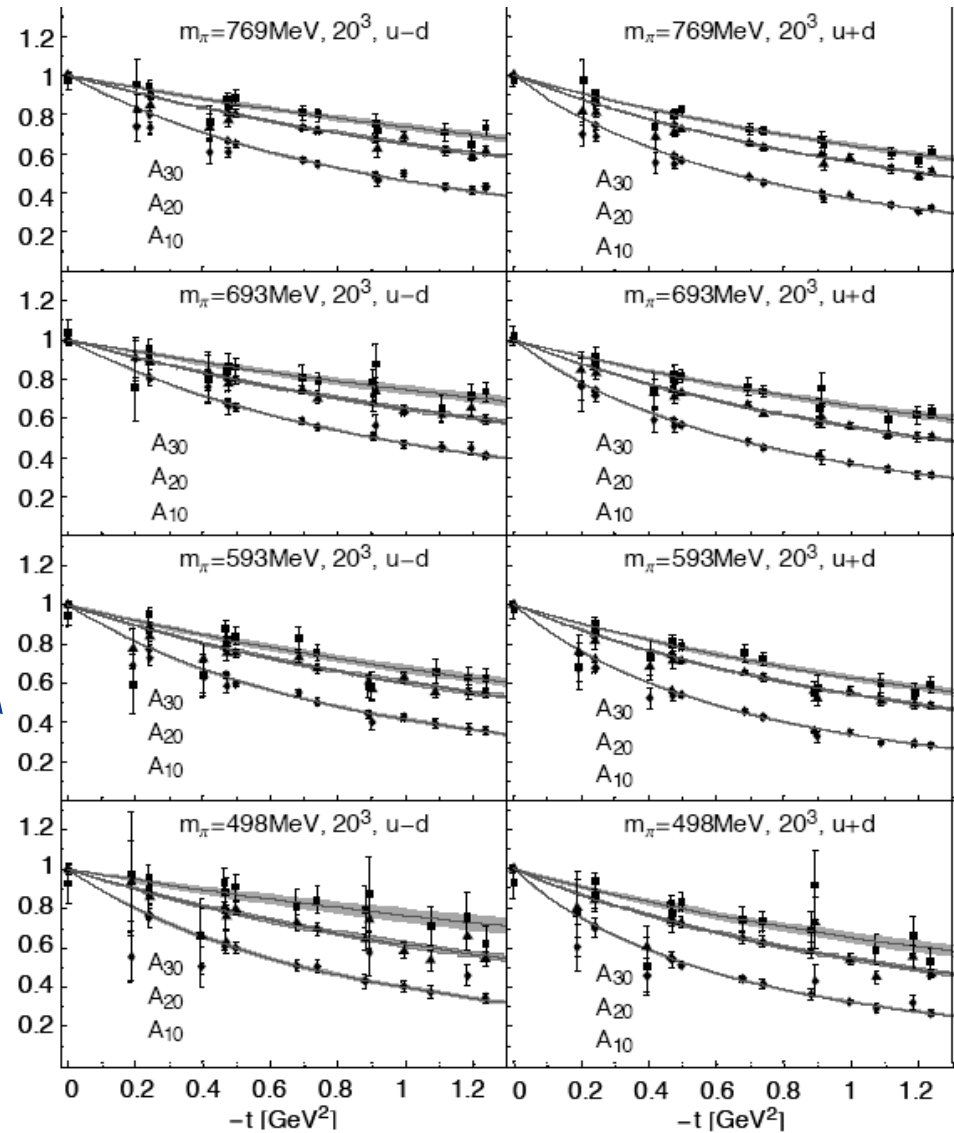
Lattice: Transverse distribution and GPDs



Lattice consistent with
narrowing of transverse
size with increasing x

Increasing n

$$A_n(t) = \frac{1}{(1 - t/M_n)^2}$$

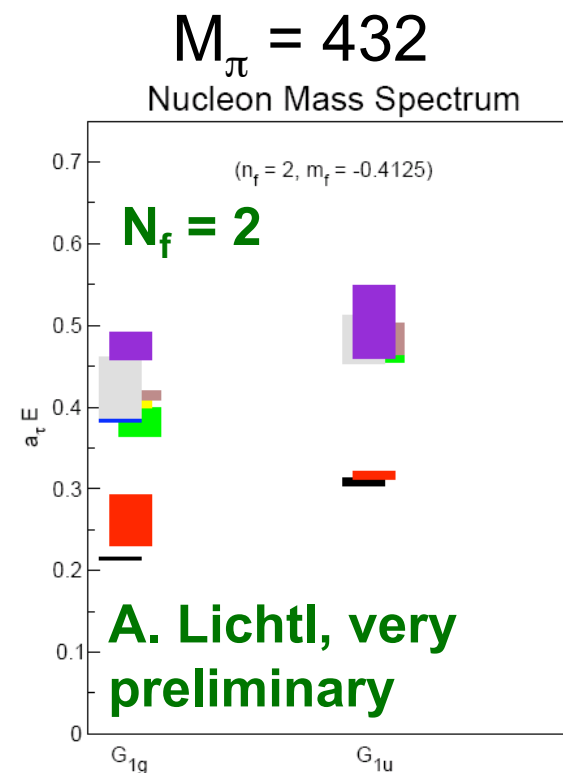
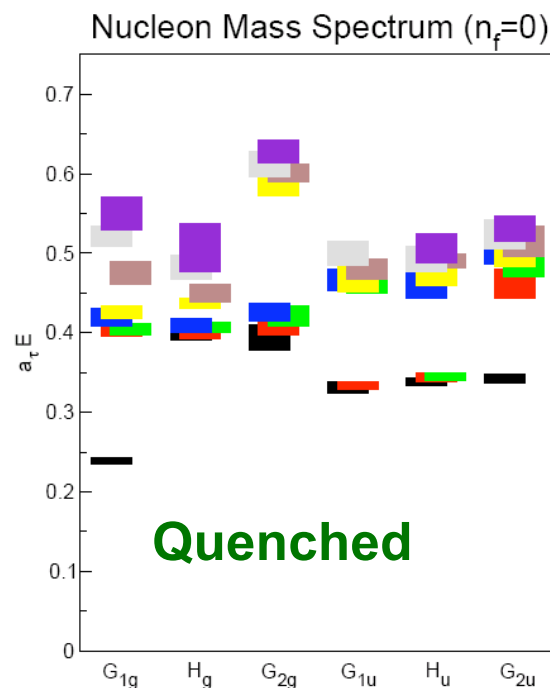
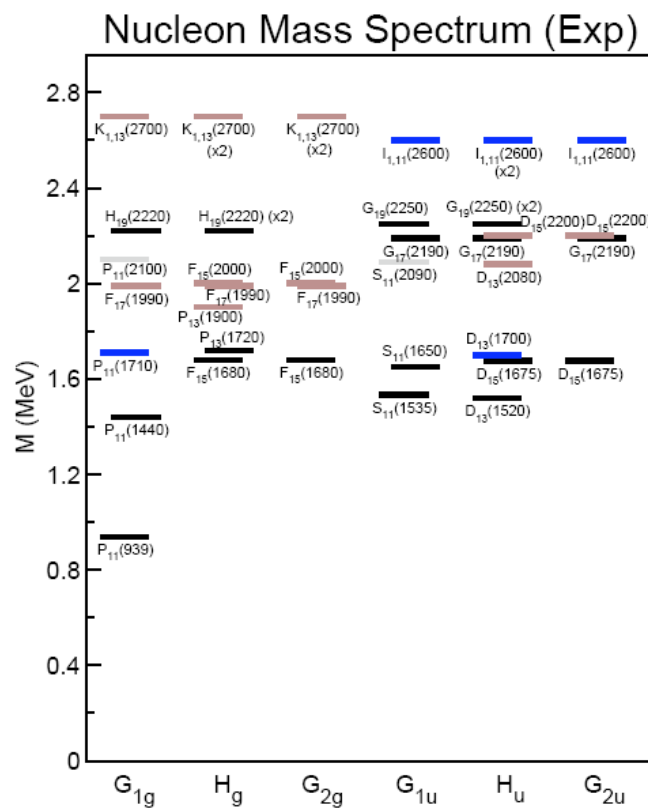


Lattice: New Initiatives

- **LHPC** joining with RBC and UKQCD
Collaborations to generate DWF lattices having the correct chiral symmetry: **major advance** in studying **hadron structure**, achieved through **improved algorithms**, **national facilities**, and **national/international collaboration**.
- **Major new initiative** of USQCD, **developed by JLab group**, to generate **dynamical anisotropic clover lattices** for spectroscopy and NN physics.

USQCD: Largest award of 10 £
10⁶ processor-hours under DOE
INCITE Program (PI: **Edwards**)

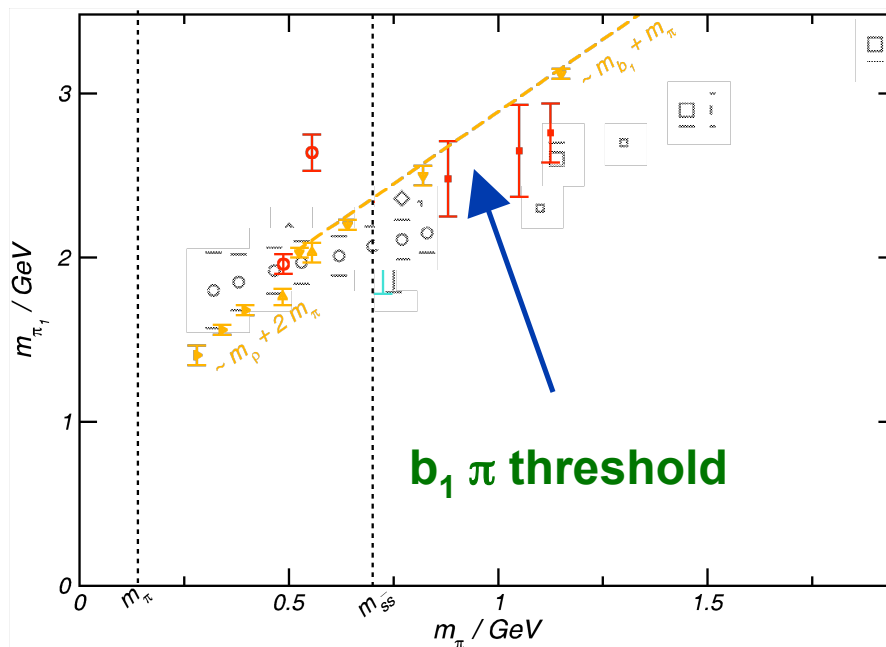
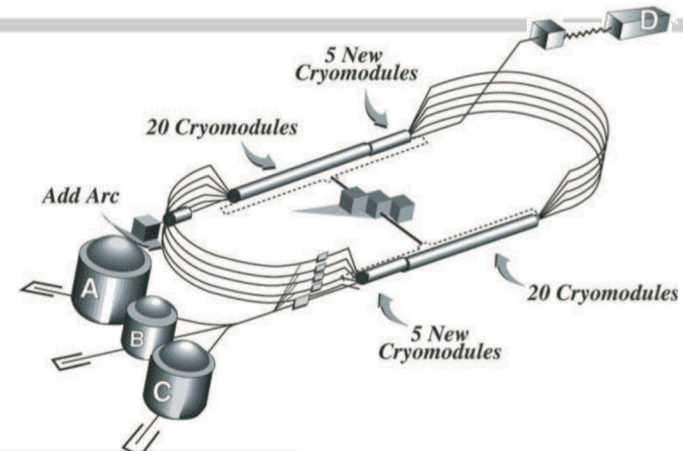
Lattice: Glimpsing nucleon spectrum



- Operators identified in quenched study are successful in full QCD
- No clear evidence for multi-particle contributions (finite volume!)
- **Emergence of Roper resonance at light-quark ma?**

Lattice QCD: Hybrids and GlueX - I

- GlueX aims to **photoproduce** hybrid mesons in Hall D.
- Lattice QCD has a crucial role in both **predicting the spectrum** and in **computing the production rates**

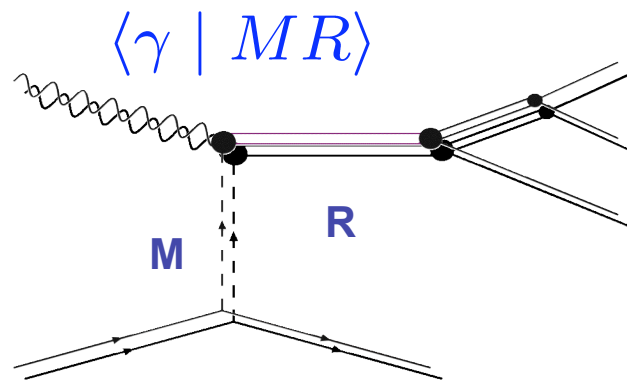


- MILC qnch Wilson $\beta=5.85$
- MILC qnch Wilson $\beta=6.15$
- UKQCD qnch Clover $\beta=6.0$
- SESAM $N_F=2$ Wilson $\beta=5.6$
- MILC qnch Stag.
- MILC $N_F=3$ Stag.
- MILC $N_F=2+1$ Stag.
- CSSM qnch FLIC
- UKQCD $N_F=2$ Clover
- UKQCD $N_F=2$ $b_1\pi$
- MILC $N_F=3$ $b_1\pi$
- MILC $N_F=3$ $\rho\pi\pi$

- Only a handful of studies of hybrid mesons at light masses – mostly of 1^{-+} exotic

Lattice QCD: Hybrids and GlueX - II

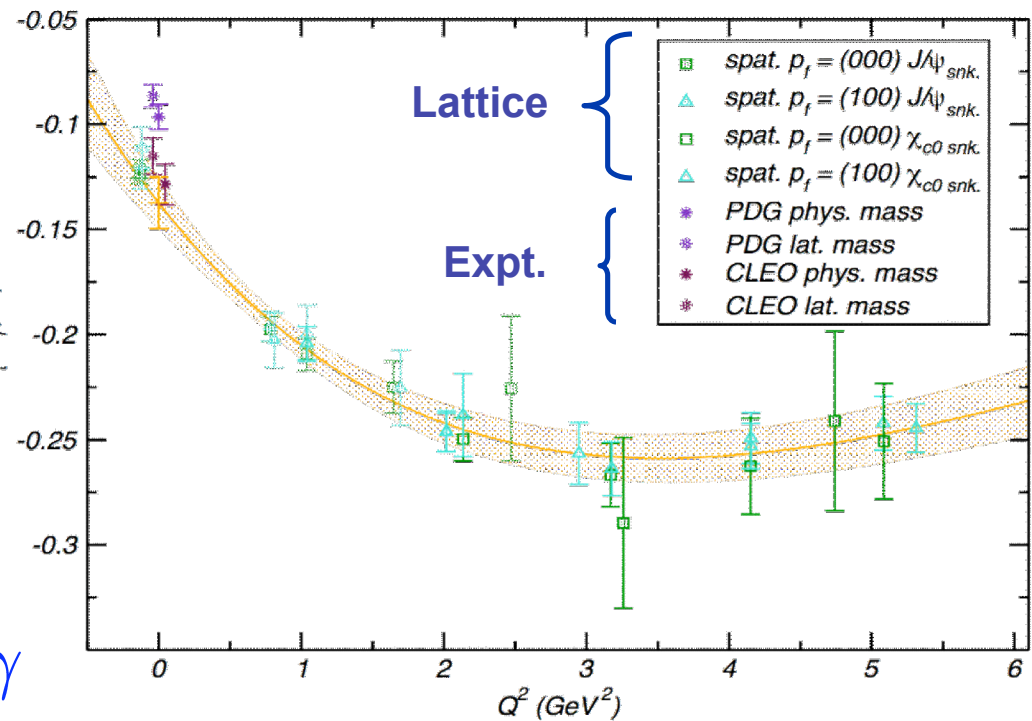
- Lattice can compute **photocouplings**: pioneered at JLab.
- Initial computations in charmonium



Dudek, Edwards,
Richards, PRD73,
074507

$$\chi_{c0} \rightarrow J/\psi \gamma$$

PDG
CLEO
lat.



cc ! $\gamma\gamma$: Dudek, Edwards, PRL97, 172001 (2006)

Conclusions

- JLab Theory Center has major impact in **inspiring**, **facilitating**, and **interpreting** the JLab program.
- Recent initiatives coming to fruition – Lattice QCD, EBAC – and new theoretical focus on GlueX
- Impact of Theory Center seen in both publications in high-impact journals, and invited talks at major conferences